

Redshifts of the Gravitational Lenses MG 1131+0456 and B 1938+666¹

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ABSTRACT

The redshifts of the gravitational lens galaxies in MG 1131+0456 and B 1938+666 are 0.844 and 0.881 respectively. Both are early-type galaxies lying at the redshifts predicted by assuming that they are early-type galaxies with old stellar populations lying on the fundamental plane. We also find evidence for a foreground group of galaxies at $z = 0.343$ near MG 1131+0456. The source redshifts are predicted to be $\gtrsim 1.8$ in both systems, but they are so red that infrared spectra will be required to determine their redshifts.

Subject headings: *cosmology — distance scale — gravitational lensing*

¹Based on observations at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California

1. Introduction

There are now over 50 multiple-image gravitational lens systems. The lens sample is a unique and powerful tool for studying cosmology, galactic structure, and galactic evolution. For studying galaxy structure and evolution: (1) it is the only sample of galaxies selected based on mass rather than luminosity; (2) it is one of the largest samples of galaxies with precisely measured masses; (3) it is comparable in size to the largest kinematic samples outside the local universe. The lenses are one of the more promising alternatives to measuring H_0 other than using the local distance ladder (see Koopmans & Fassnacht 1999), and their incidence and redshift distributions can be used to measure the underlying geometry (Ω_0 , Λ_0 , see Falco, Kochanek & Munoz 1998). They can also be used to study the hosts of high-redshift AGN and quasars (Rix et al. 1999) and the dust (Falco et al. 1999a) and interstellar medium (e.g. Menten, Carilli & Reid 1998) of the lens galaxy. Surveys to find new lenses are now very productive (e.g. Browne et al. 1999), and HST imaging surveys are providing detailed surface photometry for most of the lens galaxies (Falco et al. 1999b). Thus, the remaining barrier to exploiting the astrophysical potential of gravitational lenses is the high fraction of unmeasured lens and source redshifts. In this paper we determine the lens galaxy redshifts of MG 1131+0456 and B 1938+666.

MG 1131+0456 (Hewitt et al. 1988) is a radio-selected lens, and it was the first Einstein ring to be discovered. The radio map (Chen & Hewitt 1993) shows two images of the radio core, an elliptical ring image formed from the jet, an unlensed radio lobe, and a central, unresolved image at the position of the lens. Ground-based optical (Hammer et

al. 1991) and infrared (Annis 1992, Larkin et al. 1994) established that the system was very red, but HST imaging was required to understand the morphology (Kochanek et al. 1999a). At optical wavelengths the emission is dominated by a red, early-type lens galaxy with a photometric redshift of $0.84 < z_l < 1.01$ (Kochanek et al. 1999b). There is a faint, incomplete optical ring image of the host galaxy of the radio AGN. In the infrared, the H-band image is dominated by a bright, complete Einstein ring image of the AGN host galaxy ($H \simeq 17.4$ mag). The AGN host appears to be a very dusty galaxy, which would be classified as an ERO (“extremely red object”, e.g. Thompson et al. 1999), while the lens galaxy is a normal, transparent early-type galaxy. Hammer et al. (1991) proposed a redshift of 0.85 for the lens galaxy.

B 1938+666 (King et al. 1997) was also radio-selected. The radio map shows a partial Einstein ring formed from four images of the radio jet and two offset images of the radio core. Like MG 1131+0456, ground based optical and infrared imaging found that the system was very red (Malhotra, Rhoads & Turner 1997) The lens galaxy again appears to be a red, early-type galaxy with a photometric redshift of $0.81 < z_l < 1.04$, with no sign of any optical images of the source (Kochanek et al. 1999b). In the infrared, roughly equal amounts of flux come from the lens galaxy and an almost perfectly circular Einstein ring image of the AGN host galaxy (King et al. 1998).

By modern standards, neither lens galaxy is faint ($I=20.8$ and 21.5 mag respectively). The measurement is difficult only because the spectral features of early-type galaxies at $z \gtrsim 0.7$ are buried in the Meinel OH bands. The source redshifts, however, are almost certainly

unmeasurable in the optical – the emission is very faint and dominated by the host galaxy rather than an AGN. In §2 we report measurements of the lens redshift in MG 1131+0456 and in B 1938+666. We discuss the consequences of the measurements in §3.

2. Observations and Reductions

MG 1131+0456 was observed on 11 and 12 May 1999 using the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) at the Keck-2 telescope on Mauna Kea. Both nights were clear and the seeing was variable, but extremely good ($< 0''.5$) on the night of 11 May. We used a $1''.0$ slit combined with the 400 l/mm grating blazed at 8500\AA , to obtain spectral coverage from 6250 – 10050\AA with a spectral resolution $\simeq 5\text{\AA}$ FWHM and a scale along the slit of $0''.211/\text{pixel}$. The MG 1131+0456 observation totaled 3900 seconds on the lens, and serendipitously caught three other galaxies, G1, G2, and G3, at the same time. The slit was oriented at a position angle of 63° , as illustrated in Figure 1.

B 1938+666 was observed on 26 and 27 October 1997, and again on 23 July 1998. The October nights had light cirrus and $\sim 1''$ seeing; July was clear and had excellent seeing of about $0''.6$. In October 1997 the grating was rotated to provide coverage from 3800 – 8700\AA with a spectral resolution $\simeq 7.9\text{\AA}$ FWHM; in July 1998 the 400 l/mm grating was used over the range 5250 – 9050\AA with a spectral resolution $\simeq 5\text{\AA}$ FWHM. The much improved seeing in July resulted in much more signal for the lensing galaxy, so the analysis of the lens galaxy is based only on those data. Figure 1 shows the two slit positions which were used. At PA 96 (October 1997) the slit caught galaxy G2 which showed [OII] emission, and at PA 133 (July 1998) the slit also caught

galaxy G1.

The observing program was similar in all respects to that of Tonry (1998), and the same template stars were used for the redshift determinations reported here. A log of the observations is presented in Table 1.

The spectra were reduced using software described in detail by Tonry (1984). The basic steps are to flatten the images, remove cosmic rays, derive a wavelength solution as a function of both row and column using sky lines (wavelengths tabulated by Osterbrock et al. 1996), derive a slit position solution as a function of both row and column using the positions of the template star images in the slit, rebin the entire image to coordinates of log wavelength and slit position, add images, and then sky subtract. A linear fit to patches of sky on either side of the object (including a patch between for the galaxy pair observations) did a very good job of removing the sky lines from the spectra. In each case the spectrum was extracted, and cross-correlated with the template spectrum according to Tonry and Davis (1979), as well as being analyzed by the Fourier quotient method of Sargent et al. (1977). The cross-correlation is more robust in the case of low signal to noise, but at the signal levels here the two results are statistically the same, and are simply averaged. For each spectrum the redshift and error were calculated. Table 2 lists the redshifts, errors, and cross-correlation significance “ r ” values for each spectrum or emission lines used for redshift determination.

Fig. 1.— Illustration of the slit positions and galaxy identifications for MG 1131+0456 and B1938+666. North and East are indicated in each diagram as well as a $10''$ scale.

2.1. MG 1131+0456

The spectrum of the lens galaxy in MG 1131 is that of a typical early-type galaxy at a redshift of $z_l = 0.8440 \pm 0.0005$. With a cross correlation r value of 7.6, the redshift is determined to a high degree of confidence, and it is confirmed by the H and K lines visible at 7300Å and the weak [OII] emission. The spectrum is illustrated in Figure 2. No hint of source galaxy features could be discerned in the spectrum.

The other three galaxies caught in the slit, G1, G2, and G3, are part of a group or cluster at redshift 0.343; G1 is an early-type galaxy, whereas the spectra of G2 and G3 are dominated by very strong emission lines.² The velocity dispersion of the cluster inferred from these three galaxies is only 233 km s⁻¹, but it seems likely that this is quite a rich group given that the slit happened to pick up three at once. This is in addition to the group or cluster which seems to be associated with the lens galaxy (see Kochanek et al. 1999a)

2.2. B 19381+666

The poor seeing in the 1997 observing run precluded determination of a redshift for the B1938 lensing galaxy, although features which might be construed to be H and K were found at $z = 0.88$. The galaxy G2, which was placed in the slit at PA 96, has a single, strong emission line which is almost certainly [OII] at a redshift of 0.8784, judging from its width and isolation. Revisiting the lensing galaxy in 1998 under conditions of good seeing soon provided a spectrum which shows that it has

²In the labeling scheme used by Kochanek et al. (1999a), our galaxy G1 is their galaxy G2, and our galaxies G2 and G3 lie outside the field of view of their HST images.

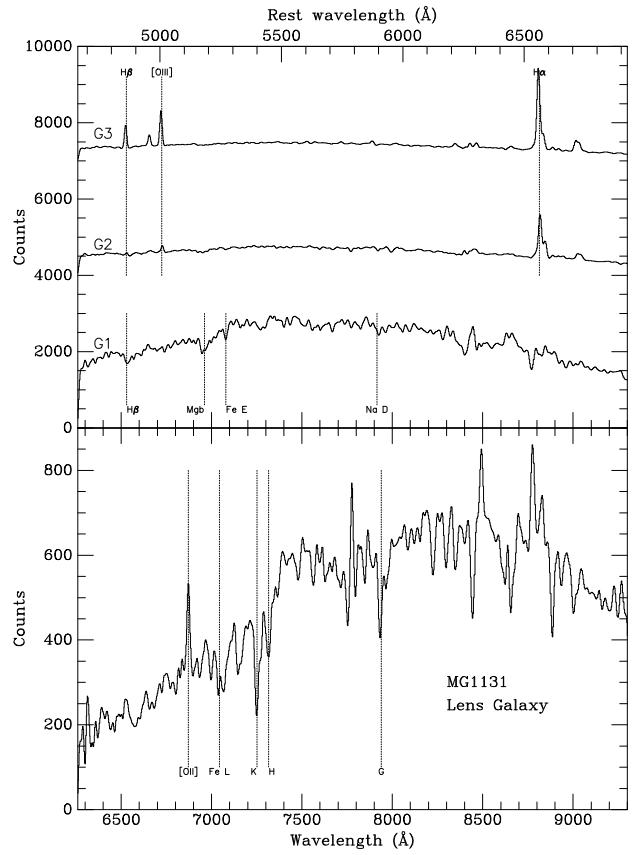


Fig. 2.— The spectra of the lensing galaxy in MG 1131+0456 and the neighboring galaxies G1, G2, and G3 are shown. The spectra were smoothed with a FWHM 9Å Gaussian. The top axis shows rest wavelength at the redshift of 0.343 of the neighboring groups, and some emission and absorption lines are marked. The lensing galaxy is shown in the bottom panel, and various absorption lines and the [OII] 3727 line are marked. Most of the prominent features beyond 8400Å are poorly subtracted sky lines. The atmospheric A and B bands have been divided out of the spectrum. For clarity, the spectra of G2 and G3 have been divided by 3 and offset by 4000 and 7000 counts respectively.

a redshift of $z_l = 0.881 \pm 0.0005$. These spectra are plotted in Figure 3. Again, no hint of source galaxy features could be spotted.

We list in Table 2 a tentative redshift of 0.924 for galaxy G1, which lay in the PA 133 slit, but the r value of only 3.9 makes it very possible that this redshift is not correct.

3. Discussion

The MG 1131+0456 and B 1938+666 lens galaxies are normal, passively evolving early-type galaxies at $z_l = 0.844$ and 0.881 respectively. We see this directly in their spectra. The spectroscopic redshifts agree very well with the photometric redshift estimates of Kochanek et al. (1999b) based on the fundamental plane of lens galaxies and the agreement of the broad band colors with passively evolving models of stellar populations.

With the lens redshift known, we can use the fundamental plane to estimate the source redshift. The limits will be imprecise because the position of the lens galaxy relative to the fundamental plane depends on the source redshift only through the effects of the weakly varying distance ratio D_{LS}/D_{OS} on the inferred velocity dispersion of the lens galaxy (see Kochanek et al. 1999b). The estimated velocity dispersion, $\sigma^2 \propto D_{OS}/D_{LS}$, is divergent at the lens redshift and monotonically declines with increasing source redshift. Thus, we obtain firm lower bounds of $z_s > 1.9$ and $z_s > 1.7$ for the source redshifts of MG 1131+0456 and B 1938+666 respectively. There is no firm upper bound for the redshift of either source over the range we considered ($1 < z_s < 5$). For MG 1131+0456 there is no statistically significant estimate for a best source redshift, while for B 1938 we estimate that $z_s = 2.8$. In both systems, the optical counterparts of the source are too faint

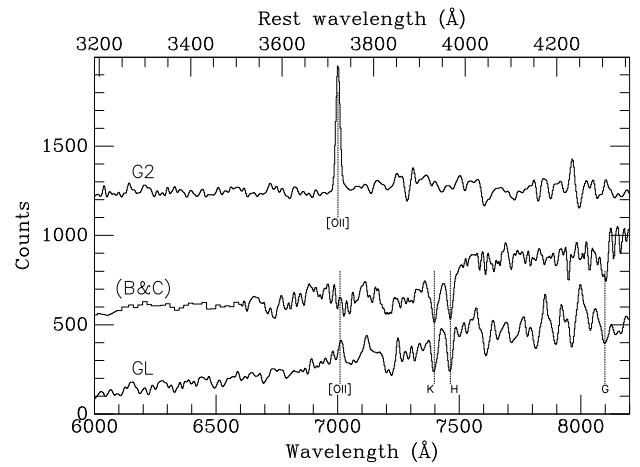


Fig. 3.— The spectra are shown for G2 and the lensing galaxy in the B 1938 system. These spectra have been Gaussian smoothed with a FWHM of 9 \AA . The top axis shows rest wavelength at a redshift of 0.881. A single strong emission line in G2 is probably [OII] 3727, and it is also faintly visible in GL. The middle curve is a Bruzual & Charlot 1997 spectrum of a 10 Gyr single burst model, and illustrates how many of the UV features seen in GL between O[II] and Ca K are real. For clarity, G2 has been offset by 1100 counts.

for redshift measurements, but both should be measurable with the new generation of infrared spectrographs. MG 1131+0456 is very bright in the infrared and the counterparts of the radio cores become steadily brighter at longer wavelengths (see Larkin et al. 1994) as the dust in the host galaxy becomes increasingly transparent. B 1938+666 is more challenging because it is fainter and lacks obvious counterparts to the radio cores. Both hosts are examples of extremely red galaxies which probably would be missed in surveys based on the “UV-dropout” method.

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TABLE 1
OBSERVING LOG.

Obs#	Objects	UT Date	UT	sec <i>z</i>	PA	Exposure	Grating
1.	B 1938	26/10/97	04:59	1.18	96	1500	300/5000
2.	B 1938	26/10/97	05:25	1.44	96	1500	300/5000
3.	B 1938	27/10/97	04:47	1.08	133	1500	300/5000
4.	B 1938	27/10/97	05:15	1.38	133	1500	300/5000
5.	B 1938	23/07/98	06:04	1.97	133	1500	400/8500
6.	B 1938	23/07/98	06:33	1.83	133	1500	400/8500
7.	B 1938	23/07/98	07:01	1.73	133	1500	400/8500
8.	B 1938	23/07/98	07:31	1.63	133	1500	400/8500
9.	MG 1131	11/05/99	06:50	1.03	63	1200	400/8500
10.	MG 1131	11/05/99	07:11	1.04	63	1200	400/8500
11.	MG 1131	11/05/99	06:29	1.03	63	1500	400/8500

NOTE.—PA is east from north, exposures are in seconds.

TABLE 2
REDSHIFTS AND EMISSION LINES.

Galaxy	<i>y</i>	<i>z</i>	\pm	<i>r</i> /emission
MG 1131 GL	0.0	0.8440	0.0005	7.6 [OII]
MG 1131 G1	15.6	0.3438	0.0002	5.0
MG 1131 G2	31.0	0.3437	0.0002	[OII] [*] ,H β ,[OIII],H α ,[NII],[SII]
MG 1131 G3	75.3	0.3420	0.0002	[OII] [*] ,H β ,[OIII],H α ,[NII],[SII]
B 1938 GL	0.0	0.8809	0.0005	5.9 [OII]?
B 1938 G1	4.4	0.924?	0.001	3.9
B 1938 G2	9.5	0.8784	0.0005	[OII]

NOTE.—Columns: Galaxy name, slit position ("), redshift and error, cross-correlation *r* value or emission lines (* indicates second order)

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